EXTREME-ULTRAVIOLET OBSERVATIONS OF SUNSPOTS WITH THE HARVARD SPECTROMETER ON THE APOLLO TELESCOPE MOUNT


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Received 1974 July 30; revised 1974 August 13

ABSTRACT

EUV spectroheliograms show that the areas directly above sunspot umbrae are the brightest features in an active region by an order of magnitude in the chromosphere-corona transition region ($10^5 \text{ K} < T < 10^6 \text{ K}$). Ratios of density-sensitive lines in the transition region show a significant decrease in gas density over the umbra relative to surrounding plage. We deduce that the temperature gradient in the transition region over the spot is decreased by an order of magnitude or more, relative to the plage.

Subject headings: chromosphere, solar — corona, solar — spectroheliograms — sunspots

I. INTRODUCTION

The results reported in this Letter were obtained with the photoelectric extreme-ultraviolet (EUV) spectrometer operated on the Apollo Telescope Mount (ATM) by the Harvard College Observatory. The capabilities of the instrument and its calibration are described in more detail by Reeves, Timothy, and Huber (1974).

We report here on observations of two sunspots: one (in McMath 12417, central meridian passage 1973 July 5) was an unusually large preceding spot associated with bright Ca K plage, and the other (in McMath 12543, CMP 1973 October 2) was a large single spot with little associated plage. The monochromatic raster pictures discussed here were obtained in the spectral range between 300 and 1400 Å with a spectral purity of 4 Å and a spatial resolution of 5″. These observations permit us to spatially resolve and study photometrically for the first time the EUV emission above the sunspot itself.

II. OBSERVATIONS

Figures 1 and 2 (plates L5 and L6) show the appearance of the two spots in lines and continua formed at temperatures ranging from less than $10^4 \text{ K}$ (Hα, Ca ii K) to about $1.5 \times 10^6 \text{ K}$ (Mg x λ625). Table 1 lists the emissions, ions, and best estimates of the value of $T_{\text{max}}$ for the radiations referred to in this paper. ($T_{\text{max}}$ is defined as the temperature at which the contribution function for the fine emission is at a maximum. For fines in the transition zone, it is approximately the temperature at which the expression, $N_i/N_{\text{tot}} \exp \left(-\Delta E/kT\right)$, attains its maximum value for a line of excitation energy $\Delta E$ in the ith stage of ionization of an element whose total density is $N_{\text{tot}}$). The values of $N_i/N_{\text{tot}}$ are taken from calculations of Dupree (1974). The EUV raster pictures given in figures 1 and 2 were generated on a computer-driven cathode ray tube system from photoelectric digital data. In figure 1, the projection angle between the normal to the solar surface and the line of sight is about 45°; in figure 2 the projection angle is only about 18°. Also shown are Hα, Ca ii K (fig. 1), and magnetic field (fig. 2) data for the same regions.

It can be seen from figures 1 and 2 that the sunspot is the brightest feature in the active region in emission lines formed between $10^5 \text{ K}$ and $10^6 \text{ K}$. Tracings across the spots reveal that in the upper chromosphere (La λ1216, helium continuum λ503, C ii λ1335) the enhancement over the umbra is not significant compared with the enhancements in the plage. In C iii, localized enhancement appears at the center of the umbra in both spots, with an intensity comparable to that of the nearby plage. However, in O iv, O vi, Ne vii, and Mg viii the intensity exceeds the plage intensity by an order of magnitude. In Mg x, the spot emission is unremarkable once again, with an enhancement of perhaps a factor 2 over the surrounding corona. Figure 3 shows traces across the umbra of the spot shown in figure 2 to illustrate some of these conclusions.

The intensity tracings across the spot at all temperatures show a smooth, single peaked, roughly symmetrical profile whose spatial half-power width is comparable to the cross-section of the photospheric umbra ($45° \times 25°$ and $20° \times 20°$ for the spots in figs. 1 and 2.)
FIG. 1.—McMath region 12417, seen at N15 E42 on 1973 July 2. The field of view is 5 arc minutes square. The optical photoheliograms were kindly provided by Big Bear Solar Observatory; they are simultaneous to within 1 minute and were taken during the same time interval in which the EUV rasters were obtained, between 13:47 UT and 18:43 UT.

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Fig. 2.—McMath region 12543 seen at N14 E11, on 1973 October 1. The Hα photoheliogram was taken at the Culgoora Solar Observatory, and the magnetogram was obtained at Kitt Peak National Observatory.

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Fig. 3.—Intensity profiles across the umbra of the spot shown in Fig. 2. S marks the location of the spot umbra, and P the location of the adjacent weak plage. The counts are normalized to \( \langle C \rangle \), the average count level over the whole raster picture.

respectively). In figure 4 we plot the half-intensity width of the spot emission curves against \( T_{\text{max}} \). It is seen to increase in cross-section with increasing \( T_{\text{max}} \), above a minimum in the lower transition zone. It is interesting to note that the minimum half-width is definitely smaller than the diameter of the umbra in the photosphere. In addition, the peaks of the profiles in and above the transition zone are mutually coaligned to within 5\(^\circ\) and fall within and close to the center of the large photospheric umbra. As seen from figure 3, the value of the intensity ratio \( r(C \text{ m}) = I(C \text{ m } \lambda 1176)/I(C \text{ m } \lambda 977) \) shows a decrease over the umbra relative to the nearby plage. This ratio has been shown to be a monotonically increasing function of density, as is the corresponding ratio in \( O \text{ v} \), \( r(O \text{ v}) = I(O \text{ v } \lambda 760)/I(O \text{ v } \lambda 630) \) (see Munro, Dupree, and Withbroe 1973). We have examined the ratios \( r(C \text{ m}) \) and \( r(O \text{ v}) \) in 15 ATM spectra of one sunspot umbra, obtained over a time interval of three days, and 15 spectra of plages obtained during the same time interval. We find \( r(C \text{ m}) \) (umbra)/ \( r(C \text{ m}) \) (plage) = 0.76 ± 0.06 and \( r(O \text{ v}) \) (umbra)/ \( r(O \text{ v}) \) (plage) = 0.73 ± 0.07, where the errors quoted are standard deviations of the mean. Calibration of the intensity ratio in terms of electron density is uncertain (Jordan 1974), so we do not quote the exact size of the density decrease. Nevertheless, the decrease of the intensity ratio is significant. If the density is decreased at all in the transition zone, then the increase of brightness by a factor of 10 for lines such as \( O \text{ iv} \) implies an increase by more than a factor of 10 in the thickness of the region emitting these lines. Consequently, the temperature gradient in the transition region is at least an order of magnitude lower over the spot than over the plage.

Assuming as a first approximation that all lines in the transition zone between \( 2 \times 10^{5} < T_{\text{max}} < 10^{6} \) are enhanced by a factor of 10 over the umbra, we may estimate the radiative loss from this region as \( \sim 10^{6} \) ergs cm\(^{-2}\) s\(^{-1}\). This is a factor of \( \sim 10^{4} \) of the missing umbral photospheric radiation. It is also interesting to note that neither the chromosphere nor the corona directly over the umbra shows significant enhancement of radiation. Thus the existence of the observed increase in emission over the spot may give us some clues in determining where the missing energy is dissipated, but it is of no direct consequence itself to the total energy balance of the spot, a fact which has most recently been pointed out by Parker (1974).

From the observation that the cross-section of the spot increases with \( T_{\text{max}} \) we conclude that the magnetic field diverges with height over the umbra. This can be seen directly from the loop structures in \( Ne \text{ vii} \) which emanate from the spot in figures 1 and 2. However, the
increase of diameter with height may not be due simply to the spreading of filed lines into a current-free configuration, since the observed configurations of chromospheric fine structures around spots suggest strongly that the magnetic field in the chromosphere over a spot is not in fact, current-free (Nakagawa and Raadu 1972).

We are indebted to the astronauts of the three Skylab crews and to the multitude whose efforts at the ground support facilities made these observations possible. This work was supported under contract Nas 5-3949.

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